Cryo-Cooled Sapphire Oscillator for the Cassini Ka-band Experiment*

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ABSTRACT

We present features for an ultra-stable sapphire cryogenic oscillator which has been designed to support the Cassini Ka-band Radio Science experiment. The design of this standard is new in several respects. It is cooled by a commercial cryocooler instead of liquid cryogens to increase operating time, and it uses a technology to adjust the temperature turn-over point to extend the upper operating temperature limit and to enable construction of multiple units with uniform operating characteristics. Objectives are 3×10^{-15} stability for measuring times 1 second $\leq \tau \leq$ 100 seconds, phase noise of -85 dBc/Hz from offset frequencies of 1 Hz to 1000 Hz at 10GHz carrier frequency, and a one year continuous operating period.

BACKGROUND:

Cryogenic oscillators make possible the highest stability available today for short measuring times ($\tau \leq$ 100 seconds)[1,2,3]. However, they have so far proven impractical in applications outside the research environment due to their limited operating periods. Interruption of normal operation is typically required while a cryogen is replaced, the system then returning to nominal operation as temperatures settle down to a stable operating condition. It is ironic that these standards, while optimized for ultra-high stability at short operating times, must operate for periods of a year or more without interruption to be considered for many applications. This is due to the fact that frequencies generated are typically used for several purposes—e.g. radio science on one hand and scheduling on another. Cryogenic standards also represent the best promise for improved L.O. performance as required by the new generation of passive atomic standards, and continuous operation is extremely desirable in such an application.

While both superconducting and sapphire resonators can provide the very high microwave quality factors (Q's) required for ultra-stable operation, whispering-gallery sapphire resonators allow somewhat relaxed cryogenic requirements—showing Q's of 10^9 at temperatures as high as 10K. However, the high Q makes possible high stability only if the frequency of resonator itself is stable, and for most cases this is prevented by frequency variation caused by temperature fluctuations. Compensation of the temperature-induced variation has been accomplished in sapphire resonators by paramagnetic spin[1,2] and mechanical[3] tuning effects. Such a technology can significantly relax temperature regulation requirements. For example, compensation cancels the first order temperature dependence of 3×10^{-10}/K at 10K, leaving a quadratic coefficient of $3.3\times10^{-9}/(K^2)$. Thus, for a stability of 3×10^{-15}, temperature regulation must be 10 μK for uncompensated sapphire compared to 1mK for a compensated one.

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OSCILLATOR DESIGN:

Use of a cryocooler limits the achievable resonator temperatures to approximately 10K. Even though ultimate temperatures for cryocoolers are somewhat below this value, several considerations additionally limit the available cooling capability. These include thermal impedances associated with the vibration isolation system, thermal regulation stages which are required to eliminate cyclic and random temperature variations, and reduction in cryocooler performance over its operating life.

Four major aspects of the design of this compensated sapphire oscillator (CSO) include:

- *A sapphire resonator compensated for operation at a temperature of approximately 10 Kelvin.* At most temperatures from 1K to 15K, sapphire's thermal variation of frequency is partially compensated by incidental paramagnetic impurities in high-quality sapphire resonator material. This effect is strongly frequency dependent for the Cr impurities typically found, due to the 11.44 GHz zero field splitting of Cr in sapphire or ruby. Recently available sapphire resonator material without Cr but containing Mo and Ti paramagnetic impurities shows excellent Q values and no observable frequency dependence to the compensation effect at X-band frequencies due to zero field splittings that are 10 or more times higher[2]. We hope to combine these mechanisms to better control the turn-over temperature and enable the construction of multiple units with similar characteristics at a common operating temperature. The issues involved in spatially disparate compensation mechanisms were successfully dealt with in our previously reported 77K CSO[3].
- *A 2-stage commercial closed-cycle refrigerator with base temperature of 5.5 Kelvin or below.* A new cooler from Leybold/Balzers allows temperatures as low as 4.2K to be achieved for the first time without using a Joule-Thompson (J/T) expansion valve[4]. The small orifice associated with this valve can clog due to impurity condensation, and elimination of the J/T valve is expected to improve long term reliability. The new cooler, for example, can maintain 6 Kelvin at the second stage with a heat load of 1.2 watts, with 15 watts simultaneously input to the higher temperature stage.
- *A vibration isolation design sufficient to effectively eliminate cryocooler vibration.* The inherent strain sensitivity of electromagnetic resonators gives rise to an acceleration sensitivity of frequency that is typically 10^{-9}/g or more. Any mechanical isolation system must involve low mechanical impedances to a stable platform combined with a high mechanical impedance between the cryocooler system and the resonator system. Such a system will also have a significant thermal impedance[5].
- *A modified Pound frequency lock circuit will be used to generate the stable output frequency.* Splitting of the high-Q line by a factor of 6×10^{6} was demonstrated by such a frequency-lock system in the 77K CSO[3]. Applied here, this could make possible a stability of 1×10^{-15} with a Q of only 1.7×10^{8}.

CONCLUSIONS:

The first unit is currently under construction with more units scheduled to be installed in three Deep Space Network stations for the Cassini Ka-band experiment starting in the year 2000. Thermal and vibration tests of cryocooler and cryostat are presently under way. Resonator optimization and test, and first frequency stability measurements are projected by June 1997.

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